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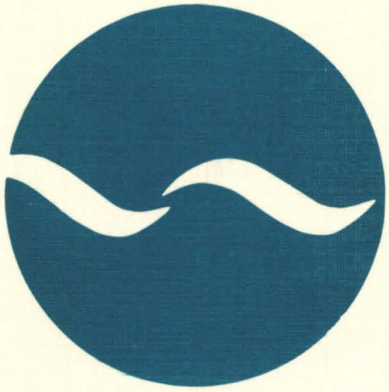
USES OF INCREASED FLOWS ORIGINATNG ON THE ARAPAHO NATIONAL FOREST (FINAL REPORT)

April 18, 1986



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USES OF INCREASED FLOWS ORIGINATNG ON THE ARAPAHO NATIONAL FOREST (FINAL REPORT)

April 18, 1986

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Boulder, Colorado

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USES OF INCREASED FLOWS ORIGINATING ON THE ARAPAHO NATIONAL FOREST (FINAL REPORT)

I. INTRODUCTION

A. Background

Watershed management research in the Southwestern United States has shown that vegetation manipulation can be used to increase streamflow (for example, Leaf, 1975; Hibbert, 1979; Troendle, 1983). Public agencies manage large land areas under multiple use guidelines, where water runoff could be increased using such vegetation management techniques. However, these practices involve costs in the form of increased management expense and possible adverse effects on existing land uses. All of the benefits and costs of streamflow augmentation must be assessed in order to determine whether implementation of such practices is warranted.

In order to calculate the benefits of increased streamflow, the effects of such increases on water uses in the basin must be predicted. The uses which may be affected include instream uses, such as fish habitat, water quality recreation, and power production, and offstream uses, principally for agricultural, municipal, and industrial purposes. Also, the re-use of the additional streamflow must be considered, because offstream users commonly return some portion of their water to the stream.

Numerous factors affect the allocation of potential streamflow increases, including institutions (laws, compacts, administrative rules and other social determinants of human behavior), water distribution networks (e.g., reservoirs, canals), economic demands for water in various uses, and hydrological regimes (with their stochastic nature). The interplay of these factors must be understood in order to predict how additional streamflow will be used.

B. Objective of Study

The overall objective of this study is to estimate or project how and where water runoff increases from vegetation manipulation in the Arapaho National Forest might affect future use of Colorado River water. Such projections inevitably are subject to many uncertainties about future conditions which could affect water use. Three sources of such uncertainty are so important in this case that they deserve explicit consideration. They are (1) changes in water allocation institutions, (2) the stochastic nature of water flows, and (3) future demand for water in municipal, industrial, and agricultural applications. The analysis must reveal how possible changes in these parameters could change projections of future water use, including increased flows.

This report (1) describes the existing water use pattern and institutional framework in the geographical areas whose water use would potentially be affected by the additional flows, (2) estimates how additional flows from vegetation manipulation would be used if current hydrologic, institutional, and water demand conditions remain unchanged, and (3) projects the ways in which water uses, including those of increased flows, might change in response to increases in water demands and changes in water allocation institutions.

C. Study Area and Time Frame

To establish a realistic context in which to study the allocation of potential runoff increases from vegetation modification in the Colorado River drainage, an area of national forest was selected. The national forest acreage in the Arapaho National Forest which drains into the

Colorado River above Kremmling, Colorado was chosen because of its proximity to experimental watersheds (Fraser Experimental Forest - see Troendle, 1983) where the effect of vegetative management on water yield has been studied. In addition, choosing this area offered an opportune location for examining the use of runoff increases in the Front Range of Colorado because of transbasin diversion facilities located on the Arapaho National Forest. Note, however, that while the Arapaho National Forest was an apt choice for study purposes, it was an arbitrary one from the standpoint of the likelihood that vegetation management for flow augmentation might actually occur.

The initial plan was to project water uses for the years 1985 and 1995. However, early analyses revealed that little change in water use could be expected in just ten years, due largely to the long time required to construct the major water projects which would be necessary to facilitate increased Upper Basin water use. Consequently, an approximate fifty-year time horizon was finally adopted. Note also that the response of the system to increased inflows will be highly non-linear so that the results of this study may not represent the effects of larger or smaller flow enhancements.

D. Approach to Analysis

The analysis performed in this study centered on the adaptation and use of two previously-developed computer models for the purposes of testing and evaluating alternative complex sets of assumptions. A network optimization model (MODSIM) was adapted to evaluate the Colorado River Basin as a whole, focusing on interstate allocation issues, while a simulation model (DWDSYM) was used to evaluate effects within the State of Colorado that may involve transmountain diversion.

II. PHYSICAL AND INSTITUTIONAL SETTING

A. Physical

The Colorado River Basin drains approximately 243,000 square miles contained within the states of Colorado, Wyoming, Utah, New Mexico, Nevada, Arizona, California, and parts of the Mexican states of Baja, California and Sonora. The river is highly regulated by a total reservoir storage capacity approximately equal to four times the river's average annual flow.

The Colorado River Basin is divided both geographically and politically at Lee Ferry, where the river crosses the Arizona-Utah border. The Upper Basin includes lands in the states of Colorado, New Mexico, Utah, and Wyoming, and is the principal source of inflow into the Colorado River system. Three major tributaries, the Green, the mainstem Colorado, and the San Juan Rivers, provide most of this inflow. The Green River drains the western flanks of the Wind River Range in Wyoming, flowing southward through northwestern Colorado and eastern Utah, and is joined by the Yampa, White, Duchesne, Price and San Rafael Rivers before meeting the Colorado mainstem within Canyonlands National Park.

The mainstem Colorado originates in the Kewaunichee Valley west of Rocky Mountain National Park and flows westward, draining most of the major mountain ranges in Colorado, and is joined by the Blue, Eagle, Roaring Fork, Gunnison, and Dolores Rivers before it meets the Green.

The San Juan River flows south and then westward from the Colorado's San Juan mountains, meeting the Colorado in southern Utah.

Below the San Juan, the Colorado enters the Lower Basin, winding through the deep gorges of Marble and Grand Canyons, and eventually emerging into more open country along the borders of Nevada, Arizona and California. A lesser amount of inflow occurs in the Lower Basin, principally via the Little Colorado, Virgin, Bill Williams and Gila Rivers.

The natural flows in the Basin are highly irregular in occurrence. While the virgin flow at Lee Ferry has averaged 14.8 million acre-feet annually over its measured period of record, flows in excess of 23 million acre-feet and less than 7 million acre-feet annually have been recorded. Over 70% of the annual virgin flow occurs in the months of May, June, and July. Flows have been recorded for less than 100 years at most points on the river.

A formidable array of reservoirs and diversion facilities alter the flow of the river. The river's two principal reservoirs, Lake Powell and Lake Mead, formed by Glen Canyon and Hoover Dams, respectively, provide over 50 million acre-feet of storage. Other major reservoirs include Lake Granby, Dillon and Green Mountain Reservoirs on the mainstem Colorado, Fontenelle and Flaming Gorge Reservoirs on the Green, the Curecanti unit on the Gunnison, and Navajo Reservoir on the San Juan.

Water is diverted from the river at hundreds of relatively small diversion points in the Upper Basin; in the Lower Basin diversions tend to be larger and considerably fewer in number. Major diversion structures in the Lower Basin include the Colorado River Aqueduct which delivers water to the Los Angeles Basin, the Granite Reef Aqueduct supplying the Central Arizona Project, and the All American Canal System bringing water to the Imperial Valley of California. Below the international boundary, Morelos Dam diverts water for irrigation in Sonora, Mexico.

The Colorado River is already one of the most fully developed in the nation. However, additional storage and diversion projects are being planned and actively pursued throughout the basin. The U. S. Department of Interior, Bureau of Reclamation, as the principal entity responsible for operation and administration of the river, maintains a list of future water supply projects and their depletions anticipated for implementation in each of the basin states. Current water development plans of the individual states generally anticipate full development of their legal entitlements by the year 2040. A listing of the potential water development projects under consideration is shown in the Appendix. More detailed descriptions may be found in USBR (1986).

B. Origins of Increased Flows

Additional runoff due to vegetation manipulation was assumed to originate from a selected area of the Arapaho National Forest. That area is located in Grand County, Colorado, and is bounded by the continental divide on the east and southeast, Rocky Mountain National park on the northeast, the Grand County line on the north to Red Slide Mountain on the northwest, and the county line on the southeast to Copper Mountain. Private land within the boundary was excluded from consideration. Of the remaining 561,000 acres of national forest land, 83,000 acres of wilderness area and designated recreation area were excluded (Table II-1). Exclusion of 30 percent of the remaining acres, because of steepness of slope or lack of treatable vegetation (in meadow), left 334,600 acres, which were assumed to be vegetated with lodgepole pine, ponderosa pine, Douglas or other firs, spruce, or aspen and available for treatment. Existing or planned diversion facilities provide the potential for diverting runoff from most of this acreage to the eastern side of the divide (Table II-1).

Table II-1. Arapahoe National Forest Drainage Area Above Kremmling

Drainage Area	Acres		
	Total N.F.	Wilderness [1]	Treatable [2]
Total National Forest	561,000	83,000	334,600
CBT	148,000	55,000	65,100
Windy Gap	271,000	66,000	143,500
Englewood Cabin/Meadow	14,000	10,000	2,800
DWB N. Fork Ranch Creek	7,000	1,000	4,200
DWB Fraser Project	54,000	0	37,800
DWB W. Fork Rep./Exch.	99,000	0	69,300
DWB Williams Fork Project	9,000	0	6,300
Williams Fork Extension	8,000	0	5,600

1. Also includes designated recreation areas.
2. Assuming 70 percent of the non-wilderness area is treatable (not in meadows nor too steep).

C. Institutional

The uses which might be made of any Colorado River runoff increases which could be produced by vegetation manipulation are dictated by a combination of factors. Foremost among these factors is the hydrologic character of the Colorado River Basin. Nearly as important are the physical changes which man has made in the basin, including both land use changes in the watersheds and the water diversion and control structures which affect flows in stream channels. Also important explanatory factors are the various demands for water which exist now and those which will exist in the future. The final set of factors which will shape future water uses is the institutional framework which has evolved over many years to order the relationships between people as they seek to exploit a limited yet common resource. Those institutions may be grouped into two broad categories: those which mediate water use conflicts between direct water users within individual states and those which mediate conflicts between units of government at the state and higher levels.

1. State water laws

State water laws in the Colorado River Basin, as in other western states, follow the doctrine of prior appropriation. This doctrine was devised in the nineteenth century when it became apparent that the riparian doctrine, inherited from the English Common Law, was unsuitable in an arid environment because it did not provide clear and secure rights to divert and use water consumptively. The new western doctrine was based upon the first-come, first-served feature adopted in the mining camps to settle conflicts over the right to exploit mineral deposits. Its three essential principles are diversion, beneficial use, and seniority. A right may be acquired for the quantity of water diverted from its natural course and put to a beneficial use. The date upon which these conditions were met establishes the seniority of the right, although that right might subsequently be lost if the conditions of diversion and beneficial use are not maintained. The seniority principle means that whenever a conflict arose between two diverters from the same body of water the one with the senior right could divert up to the full amount to which he was entitled before the holder of the junior right could divert at all.

Each of the western states has developed its own unique adaptation of appropriation doctrine, and in some a mixture of appropriation, riparian, and Spanish water law doctrines prevails. Only Colorado remains a "pure" appropriation state, in the sense that a water right can be acquired by meeting the diversion and beneficial use requirements alone. In all other states, a permit must be obtained from a state agency, although the rules governing the issuance of those permits follow the principles of appropriation doctrine. Under the doctrine of prior appropriation, water rights in principle may be freely transferrable, although they are sometimes inseparable from the land upon which the water was originally used, as in riparian doctrine, and they may not

be transferred in such a way as to impair the right of even a junior holder to historical flows. In practice, the restrictions upon free transferability are usually imposing, although often not insurmountable. It is especially notable that informal arrangements have often been adopted among water users to overcome some of the barriers to more efficient water use which water laws have erected.

Appropriation doctrine is implemented through "calls" on the river. When a water user finds that there is insufficient water in the stream to satisfy his right to divert, he can "call out" junior appropriators, i.e., force them to cease diverting to the extent necessary to permit him to divert his full entitlement, subject of course to hydrologic availability.

2. Interstate water allocation institutions

Federal legislation and judicial actions provide the ultimate recourse in deciding all interstate water disputes, as affirmed by Arizona v. California and Sporhase v. Nebraska. However, the federal government is always reluctant to intervene until the states have clearly demonstrated their inability to resolve their disputes. When such intervention does occur, the courts have attempted, since Wyoming v. Colorado, to apply the principles of the water laws of the pertinent states (in this case the doctrine of prior appropriation), unless politically more workable arrangements have been devised, such as the principle of equitable division employed by the Colorado River Compact of 1922.

The first of the institutional features which modifies or replaces prior appropriation doctrine in governing interstate water allocation in the Colorado River Basin is the Colorado River Compact of 1922. This compact apportions the flow of the river between the Upper Basin (Arizona, Colorado, New Mexico, Utah, and Wyoming) and the Lower Basin (Arizona, California, and Nevada). It applies

the principle of equitable division, in recognition of the likelihood that application of the doctrine of prior appropriation would allocate most of the river's water to the more rapidly developing states of the Lower Basin. It provides that the Upper Basin must deliver to the Lower Basin a ten-year moving average of 7.5 million acre-feet plus, if necessary, a share of the Mexican treaty obligation (which was later determined to be 1.5 million acre-feet annually). Under the 1922 compact, the Upper Basin is also prohibited from withholding water from the Lower Basin for non-consumptive purposes, i.e., hydropower generation. Similarly, the Lower Basin is prohibited from calling water down strictly for hydropower or other non-consumptive purposes. (This article of the 1922 compact may have been modified by the 1968 Colorado River Basin Project Act providing, among other things, for the development of hydropower at Glen Canyon Dam.) Many aspects of the 1922 compact are open to varying interpretation, and each basin state has held that the interpretation most favorable to it is the proper one. For a discussion of these ambiguities and possible interpretations, see Meyers (1966). The price of Lower Basin (or, more accurately, California) accession to the terms of the 1922 compact was federal construction of Boulder (later Hoover) Dam and Lake Mead, which stores water for delivery to the Lower Basin.

The second of the institutional features which modifies or replaces the principle of prior appropriation in interstate water allocation in the Colorado Basin is the Upper Colorado River Compact of 1948. This compact allocates the (unspecified) quantity of Colorado River water assigned to the Upper Basin by the 1922 compact among the states of the Upper Basin by percentage, except that Arizona's share is a fixed 50,000 acre-feet annually. Those percentages are:

Colorado	51.75%
New Mexico	12.25%
Utah	23.00%
Wyoming	14.00%

The 1948 compact establishes the rules by which the states of the Upper Basin will curtail their respective uses if and when actual shortages develop on meeting the ten-year, 75 MAF Lee Ferry obligation under the 1922 compact. It contains far fewer ambiguities than does the 1922 compact, but certain of its provisions are inconsistent with some interpretations of that earlier compact.

Allocation of Colorado River water among the Lower Basin states was not accomplished by the interstate compact. Agreement between Arizona and Califonria could not be reached and the issue was litigated before the Supreme Court. The Court's 1963 decision in Arizona v. California constitutes the third institutional departure from the application of the doctrine of prior appropriation. In its decision, the Court followed the Boulder Canyon Project Act of 1928 in awarding 2.8 million acre-feet of mainstem supplies annually to Arizona, 4.4 million acre-feet annually to California, and 300 thousand acre-feet annually to Nevada. In a dramatic victory for Arizona, the Court excluded 3 to 4 MAF of virgin flow entering the Colorado River from Arizona's tributaries from the apportionment, awarding consumptive use of these flows exclusively to Arizona and increasing Arizona's relative share of mainstem supplies. Any surplus mainstem waters were to be divided by the formula of 46 percent to Arizona, 50 percent to California, and 4 percent to Nevada. The Secretary of the Interior was to determine when surplus water was available and how any curtailments would be accomplished.

With the ratification of two interstate compacts and the Supreme Court decision in Arizona v. California, and subject to the Mexican Water Treaty of 1944, the interstate apportionment of the Colorado River was fairly complete. It remained for the operational meaning of some of those institutional arrangements to be defined. This was accomplished in 1968 when, in the Colorado

River Basin Act, the Congress instructed the Secretary of the Interior to develop and adopt criteria for the operation of the series of federal reservoirs which had been constructed to manage the river's flow. The statutory guidelines provide that the operating rules for Glen Canyon and Hoover Dams, in particular, will assure compliance with the Mexican Treaty, deliver the required 75 million acre-feet per decade to the Lower Basin states, provide carry-over storage to accomplish the first two objectives, and maintain parity in the active storage between Lakes Powell and Mead. The 1968 Act also added another significant operational constraint by making Arizona mainstem diversions under Central Arizona Project (CAP) junior to the first 4.4 MAF of California mainstem allocations, as well as to Nevada's and Arizona's non-CAP allocations. This concession cancelled out part of Arizona's victory in Arizona v. California, but was necessary to obtain California's support for Congressional authorization and funding of the multi-billion dollar CAP.

III. METHOD

A. Conceptual Framework

A formal model which can be implemented on a computer is a virtual necessity in a study such as this one because it permits rapid, repeated, and inexpensive exploration of a complex set of assumptions about the values of uncertain parameters. Two main options are available. The first is to use a generally-structured model which has been developed previously for its power in solving a prescribed class of problems. Many such general models are available. The choice of which one to select depends upon the correspondence between the characteristics of the problem under investigation and the structure of the model. After it has been chosen, such a model must be specified with empirical data derived from the situation which is under study.

The second approach is to create an entirely new model by specifying not only the empirical data or facts of the situation under study but also the mathematical representations of the relationships between those "facts." A model developed under this approach, if it is a good one, will explain the phenomena under study better than a generalized mathematical model, but it will normally be far less tractable to use. Thus, general models are often preferred for exploratory or reconnaissance investigations while situation-specific models are developed subsequently when the problem is better defined.

Considerations such as these led to the selection of a generalized network optimization model in this first phase exploration of possible uses of enhanced streamflows in the Colorado River system.

Another more specific simulation model was used to analyze that portion of the Basin within the State of Colorado above Glenwood Springs in order to explore the potential use of increased streamflows within the State of Colorado.

1. Basin-wide Analysis

A network optimization model, a member of the more general class of linear programming models, was chosen. The network optimization model is designed to reveal the most beneficial routing of a limited resource through a set of nodes and links which comprise a network, and for which alternative routings are possible. The criteria for judging benefit are incorporated in an objective function, and the resource limitations and link capacities are included in a set of constraints.

MODSIM (Shafer, 1979) is a computer program designed to route streamflows through a hydrologic system which is characterized by spatially differentiated and linked nodes at which withdrawals and inflows occur and for which withdrawal priorities can be specified. It uses the Out-of-Kilter Algorithm (Barr, Glover, and Klingman, 1974) to solve a network optimization problem. It was chosen to model the Colorado River system as a whole, and thus provides the basic analytical framework for this study.

Two different objective functions, one institutional and one economic, were used with the MODSIM program. By comparing the optimal water allocations resulting from the use of these two objective functions, all other things being equal, one can predict and evaluate the effects of water allocation institutions.

The waters of the Colorado River are currently allocated between basin states by interstate compacts, international treaties, court decisions, and operating rules for the system of federal reservoirs. As in appropriation doctrine which governs intrastate water allocation, this complex of institutions establishes a somewhat ordered relationship among claims on limited water supplies. That ordered relationship, which is largely hierarchical, is represented in the first objective function by a series of weights on the various water demands according to the priority which existing institutional arrangements established for that demand.

Changes in water allocation institutions are represented by a reordering of water use priorities, hence the assignment of different weights within the objective function. In the limiting case of complete abandonment of existing interstate allocation institutions, and assuming that alternative institutions which permit free transfer of water were to exist, market forces alone would determine water uses. Therefore, the second objective function included weights for the various water demands which were ordered in strict consistence with the marginal value of water in each respective use.

Varying the weights used in the objective function to represent alternative institutional arrangements was only one of the perturbations which were employed in order to investigate the behavior of the Colorado River system. Variation in streamflow was of interest for two reasons. First, the primary goal of the study, was to reveal how runoff increases due to vegetation manipulation might be used. All analyses were run under two sets of assumptions; with and without increased runoff from this source. Second, the performance of the storage and delivery facilities which currently exist in the basin is affected by the pattern inherent in the hydrologic trace, which means that a multi-period

analysis must be used. Consequently, reconstructed virgin flows for a 72-year period of record (1906-1977), as developed by the U. S. Bureau of Reclamation (USBR, 1983), were used as input to assess the effect of climatic variation. It is noteworthy that there exists evidence that the historic flow records for the Colorado River represent a highly peculiar period (Stockton and Jacoby, 1976). A rigorous analysis would require the use of statistical methods to synthesize a large number of equally-probable hydrologic traces which would be used in turn as input to the analytical model. This approach was not within the scope of the current study.

Still other sources of potential variation or uncertainty were present. Water demands at the various nodes and for the various uses are presently insufficient to cause some of the major interstate water allocation mechanisms of the Colorado River Basin to be invoked. Contrary to popular impressions, there is still a surplus of water in the basin. However, that surplus will surely disappear if future demands (primarily in the Upper Basin) greatly exceed present ones. In order to test the effect of increasing demand for water, two demand levels representing current and potential future conditions, were employed. Future demands were derived largely from forecasts of water development in the Upper Basin to accomodate new energy development and municipal expansion. Increased water demands in the Lower Basin were also included, even though existing institutional arrangements limit the extent to which such demands could be served by Colorado River water in the face of increased consumption in the Upper Basin.

2. Colorado Intrastate Analysis

While the modified MODSIM model was used to evaluate the effects of runoff increases on an interstate basis, it did not provide sufficient disaggregation

capability to simultaneously evaluate the effects of runoff increases on an intrastate basis (within the state of Colorado). The basin-wide model aggregates all flows and demands on the mainstem of the Colorado River above Grand Junction, which allows some demands to be satisfied in the model by flows to which they would not have physical access in the real system. In addition, aggregation conceals the finer structure of the Colorado water rights system that allocates flows in the Basin. For this purpose, DWDSYM was used. DWDSYM is a water rights accounting model which simulates the operation of the Colorado River above Glenwood Springs, including the City of Denver water supply system. Allocation of water within this sub-basin is largely influenced by a relatively senior hydropower water right located just upstream of Glenwood Springs and below the Arapahoe National Forest. DWDSYM simulates a call upon the river originating from this water right. Operating DWDSYM under assumptions of both natural and enhanced streamflows allowed for evaluation of the effects of flow increases upon water demands in the sub-basin.

B. Assumptions

As in any investigation of this kind, several assumptions were made, all of which limit or condition the validity of the conclusions which may be drawn. Five of those assumptions are:

1. Expected runoff

The hydrologic experience of the 72-year period of 1906-1977 is a valid representation of future conditions with respect to all of the statistical moments of the runoff frequency distribution, and the serial correlation of successive runoff events. It is recognized, however, that long-term hydrologic conditions may be different from the historic observations.

2. Water demands

Future water demands are well-represented by water use forecasts and plans of water development entities. Such forecasts and plans tend to assume no changes in water-use technology or cost relationships. No econometric projections of future water demands (in which such changes might be considered) were undertaken in this study.

3. Instream uses

Demands for instream water uses, such as hydroelectric powergeneration, salinity control, recreation, and environmental protection, have no effect on interstate water allocation. This is obviously invalid in the institutionally-constrained scenarios, and would be invalid in the unconstrained scenarios if water rights for such uses were to be established, as they are in fact established in the case of hydroelectric power production.

4. Linearity

All input-output relationships are linear (an assumption of the linear programming model). This assumption is reasonably valid for most aspects which were modeled, with the notable exceptions of reservoir evaporation, which was approximated with a table of estimates and linear interpolation, and channel losses. The linearity assumption would be invalid for some instream uses.

5. Aggregation

The many individual water rights in the Upper Basin, especially, could be aggregated into just a few nodes representing the major Colorado River reaches and tributaries without vitiating the conclusions of the analysis. This is believed to be largely true insofar as interstate aspects are concerned, but limits the validity of any conclusions regarding intrastate water allocation (it

is for this reason that a separate analysis of water use in the headwater region of the Colorado mainstem, including transbasin diversions to Denver and other Front Range cities, was conducted through the use of a more detailed model).

C. Detailed Descripton of the Models

1. Representation of increased runoff

The runoff increases were assumed to be the result of removal of 50 percent of the treatable area in clear cut strips (see Leaf, 1975, for a description of such a treatment).

Of greatest importance for this study was that the runoff increase reflect the stochastic nature of streamflow. Modeling the relationship between pre-increase flow and the increase was more important than accurately predicting the volume of flow increase that is possible from a given land area. Annual fluctuation in increase is largely a function of the same hydrologic factors affecting pre-increase flow. In order to adequately take into account their stochastic nature, runoff increase estimates were tied to pre-increase flow on the Colorado at Glenwood Springs (downstream from the treatment area) based on the precipitation conditions that were assumed to create the pre-increase flow.

The general approach to estimating the runoff increases to be associated with pre-increase flows was to (1) estimate treatment area annual precipitation associated with downstream flow for all years of record, (2) estimate annual per-acre runoff increase as a function of annual precipitation, (3) aggregate to total annual runoff increase from all of the treatable acreage involved, and (4) seasonally allocate the annual runoff increase. Each of these four steps is explained below.

(1) Annual precipitation for the treatment area on the Arapaho National Forest was estimated for each of the 72 years of reconstructed flow for the Colorado River at Glenwood Springs. This was accomplished with a precipitation-runoff relationship developed from data for St. Louis Creek on the Fraser Experimental Forest. St. Louis Creek is a typical site within the study area and offers the best set of comparable precipitation and runoff data. These data yielded the following relationship of annual precipitation (P) to annual runoff (RO) (n=17, R^2=0.45, standard error=2.77, significance=0.002):

$$P = 9.72 + 1.19\ RO.$$

Annual precipitation of the treatment sites was estimated from this relationship under assumption (1) that St. Louis Creek was representative of the treatment area as a whole and (2) that annual runoff at St. Louis Creek was proportional to annual flow on the Colorado River at Glenwood Springs. Proportionality was specified in relation to mean annual flow, which was 1,442,000 acre feet for the 72 years of data from the Colorado River at Glenwood Springs and 15 inches for the 37 years of runoff data from St. Louis Creek. (Note that annual runoff at St. Louis Creek also averaged 17 inches for the 17 years for which precipitation records were available.) For example, annual flow on the Colorado River at Glenwood Springs was 2,286,170 acre feet in 1912, or 1.556 times mean annual flow. Thus, annual runoff from St. Louis Creek was assumed to be 1.56 times mean annual flow on St. Louis Creek. Such a year would, via the precipitation runoff relationship, be assumed to experience an annual precipitation of 9.72+(1.19)(15)(1.56) = 37.5 inches. Table III-1 lists predicted annual precipitation (Column 2) for the

treatment area for a range of possible ratios of annual flow to mean annual flow (Column 1), and also gives the associated annuual runoff for the treatment area (Column 3).

Table III-1: Arapaho National Forest Runoff Increase

Ratio Annual Runoff to Mean Annual Runoff	Predicted Annual Precipitation (Inches)	Predicted Annual Runoff (Inches)
.26	14.4	1.4
.37	16.3	1.7
.45	17.7	1.9
.56	18.7	2.2
1.0	27.5	3.0
1.18	30.7	3.2
1.55	37.3	3.7
1.80	41.8	3.9
2.0	45.4	4.1
2.2	48.9	4.2
2.3	50.7	4.25

(2) Annual per-acre runoff increase was predicted as a function of annual precipitation using WET., the computerized version of WRENNS (Troendle and Leaf, 1980), for the average site characteristics of the treatment area, assuming a 50 percent removal of overstory in clearcut strips. Model results were modified based on professional judgment (Troendle, USDA Forest Service) to yield estimates of annual runoff increase per-acre (Table III-I, Column 3). These estimates refer to the watershed area, not to the 50 percent actually clearcut.

(3) Aggregate runoff increase was calculated by multiplying runoff increase per acre times the acreage available for treatment, (Table II-1). It was assumed that all runoff increases were diverted to the east slope and reached the Colorado mainstream or otherwise reached points of use without carriage losses, and that all vegetation treatments occurred prior to the beginning of the study period and were maintained throughout the study period.

4) Annual runoff increase was apportioned to two-week intervals based on experience at Fraser Experimental Forest (Troendle, 1983):

April	15-30	5%
May	1-14	25%
May	15-30	45%
June	1-15	25%

The end result of these four steps was a set of runoff increase estimates associated with each year of historical data usedin the simulations. Table III depicts the runoff increases and the associated pre-increase flows. The runoff increase averages 82,000 acre-feet per year, which is 0.5 percent of the mean annual flow at Lee Ferry.

2. Network representation of the Colorado River system

MODSIM utilizes an implementation of the Out-of-Kilter Algorithm developed by Barr, et.al. (Barr, Glover and Klingman, 1974) to solve a network flow problem by minimizing transportation costs (Fulkerson, 1961; Durbin & Kroenke, 1967; Clasen, 1968). The Out-Of-Kilter Algorithm solves for the optimal flow in a circulatory network among nodes, where there is a cost associated with moving a unit of flow along a link from one node to another. MODSIM utilizes the Out-Of-Kilter Algorithm by converting a tree-structured hydrologic system, with inflows, demands, outflows and storage, to a circulatory network by connecting all points of inflow and outflow to a single mass balance node. The amount of demand, storage, inflow or outflow at a node is represented by the flow in the link (or links) to the mass balance node.

Table III-2: Summary of Colorado River Flows at Glenwood Springs and Enhancements Attributable to Vegetation Manipulation. (All flows in thousands of acre-feet)

Year	Pre-Increase Flow (1)	Ratio (3)	Flow Increase (2)	Year	Pre-Increase Flow	Ratio	Flow Increase
1906	1830.142	1.265	92.342	1942	1418.779	0.980	82.592
1907	2152.856	1.488	100.738	1943	1320.109	0.912	79.138
1908	1009.710	0.698	68.271	1944	1163.561	0.804	73.657
1909	2421.804	1.674	105.835	1945	1277.902	0.883	77.660
1910	1096.538	0.758	71.310	1946	1010.573	0.698	68.301
1911	1561.997	1.079	86.039	1947	1718.602	1.188	89.440
1912	2252.102	1.556	103.222	1948	1367.101	0.945	80.783
1913	1129.960	0.781	72.481	1949	1573.474	1.087	86.285
1914	2286.170	1.580	103.747	1950	1104.663	0.763	71.595
1915	1180.466	0.816	74.249	1951	1630.680	1.127	87.508
1916	1520.818	1.051	85.159	1952	2063.631	1.426	98.417
1917	2246.652	1.553	103.139	1953	1266.892	0.876	77.274
1918	2125.943	1.469	100.038	1954	547.923	0.379	47.963
1919	987.674	0.683	67.499	1955	852.430	0.589	62.764
1920	2164.022	1.496	101.029	1956	1322.538	0.914	79.223
1921	2188.451	1.512	101.665	1957	2330.398	1.611	104.428
1922	1400.449	0.968	81.950	1958	1477.666	1.021	84.236
1923	1897.612	1.311	94.097	1959	1172.223	0.810	73.960
1924	1571.556	1.086	86.244	1960	1256.095	0.868	76.896
1925	1126.627	0.779	72.364	1961	896.978	0.620	64.324
1926	1910.300	1.320	94.428	1962	1787.420	1.235	91.230
1927	1747.267	1.208	90.186	1963	680.288	0.470	54.460
1928	2119.205	1.465	99.863	1964	982.561	0.679	67.320
1929	1965.211	1.358	95.856	1965	1756.072	1.214	90.415
1930	1215.403	0.840	75.472	1966	693.337	0.479	55.146
1931	807.923	0.558	61.164	1967	1119.588	0.774	72.117
1932	1543.218	1.066	85.638	1968	1202.125	0.831	75.007
1933	1502.214	1.038	84.761	1969	1257.857	0.869	76.958
1934	625.310	0.432	51.687	1970	1699.786	1.175	88.986
1935	1220.908	0.844	75.665	1971	1606.855	1.110	86.999
1936	1653.522	1.143	87.997	1972	1230.320	0.850	75.994
1937	1019.316	0.704	68.607	1973	1594.070	1.102	86.725
1938	1838.718	1.271	92.565	1974	1610.883	1.113	87.085
1939	1228.169	0.849	75.919	1975	1456.824	1.007	83.790
1940	955.729	0.660	66.381	1976	1031.182	0.713	69.022
1941	1271.929	0.879	77.451	1977	568.572	0.393	48.957

1 Mean annual value is 1442 with a standard deviation of 465.
2 Mean annual value is 82 with a standard deviation of 14.
3 Ratio of annual value to mean annual value.

Each link may have a cost associated with moving a unit of flow along it. It will also have an associated minimum and maximum capacity. The Out-Of-Kilter Algorithm attempts to find a set of flows in all links which minimizes the total cost of the system within the capacity constraints. Thus, by inverting costs into priorities, it is possible to rank demands, storages and outflows and use the Out-Of-Kilter Algorithm to solve for the optimum set of flows. MODSIM solves the network for one period at a time.

For this study, a network was created which represents the Colorado River Basin. Figure III-1 shows this network. Table III-3 names and describes each node. There are 35 nodes and 36 links which are used to represent the system of rivers, reservoirs and demands which make up the Colorado River System.

The model is configured to run on the basis of four seasons, as summarized in Table III-4. The operating rules for Lake Mead specify a target flood control capacity on January 1. Thus, it was necessary to have a seasonal break at that point to allow the flood control pool to be evacuated. Flood control operations and simulation are discussed in more detail below.

Enhanced flows from treated lands will contribute principally during the period from May through July. The period August through December is characterized by low flows and irrigation demands. Irrigation in the Upper Basin ends in September or October while, in the Lower Basin, it continues throughout the year. For this reason, and because much of the available data were already compiled on the basis of a water year, a seasonal break was made between September and October.

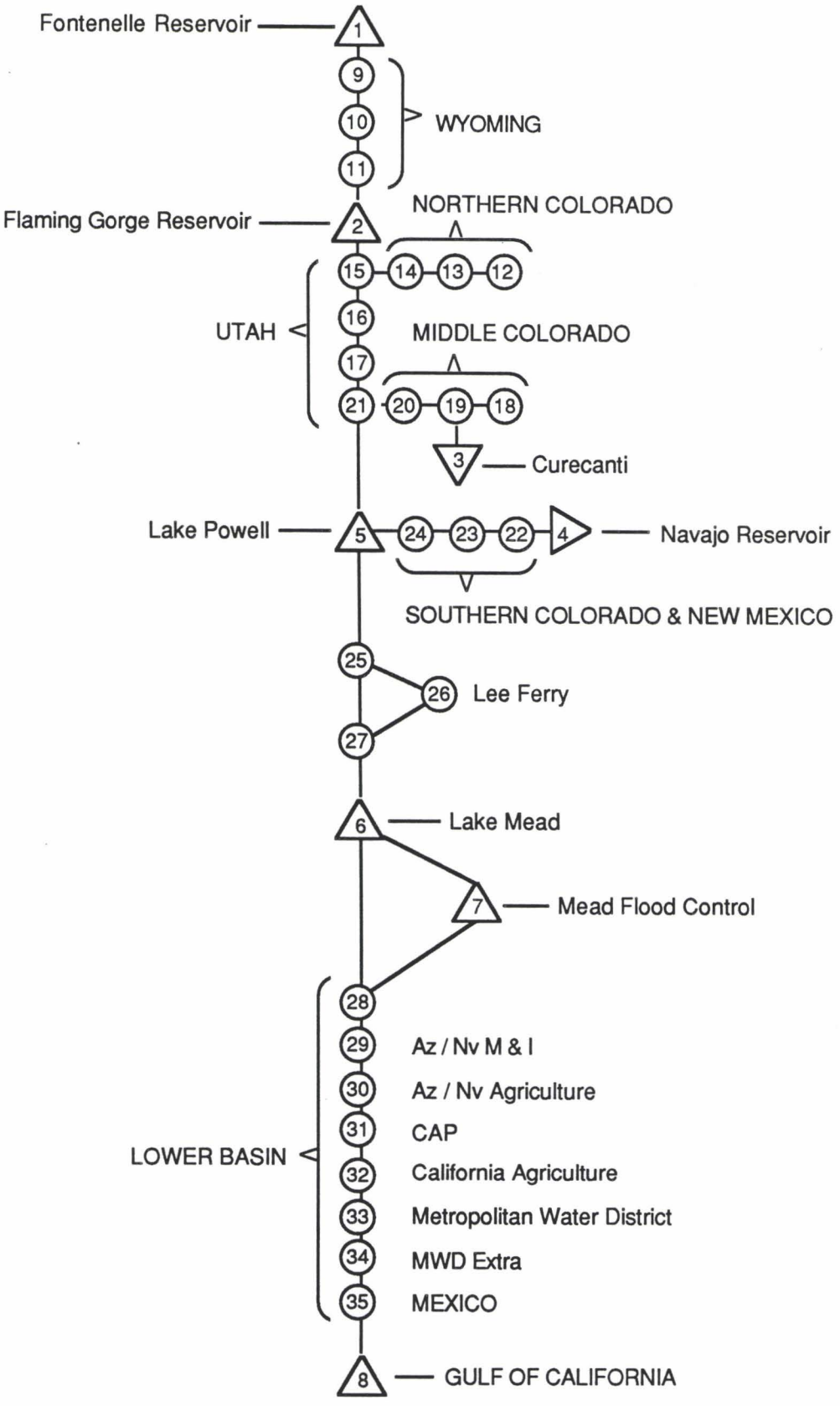

FIGURE III-1 COLORADO RIVER NETWORK DIAGRAM

Table III-3: Nodes and Descriptions

Node	Name	Inflow(3) Station	Type(4)	Constrained Rank	Unconstrained Rank	Consumption(7) Current	Consumption(7) Ultimate
1	Fontenelle	AF2112 IF2170	S,I G	38 (1)	81	0	0 (1)
2	Flaming Gorge	IF2345	S,I	40	85	0	0
3	Curecanti	IF1278 AF1246	S,I G	40	85	0	0
4	Navaho	AF3555	S,I	40	85	0	0
5	Powell	IF3800	S,G,	45	89	0	0
6	Mead Cons	AF40200 AF40210 AF41500 IF42100 IF42250 IF42750 AF42600	S,I G	75	93	0	0
7	Mead Flood	none	S	97	97	0	0
8	Gulf Calif.	none	D	85	100	60000	60000 (2)
9	Upper Green Ag	none	D	30	70	286	342
10	U.G. M&I	none	D	30	26	36	144
11	U.G. Energy	none	D	30	80	32	187
12	Yampa/White Ag	AF2600 AF2510	D I	30	70	126	138
13	Yampa/White M&I	none	D	30	20	13	39
14	Yampa/White Energy	none	D	30	32	16	21
15	West Utah Ag	AF3020 AF3065	D I,C	30	71	591	818
16	West Utah M&I	none	D	30	21	65	143
17	West Utah Energy	none	D	30	76	18	207
18	U.C. M&I	none	D	30	20	280	611
19	Upper Colo. Ag	AF0725 IF0955 IF1525	D I G	30	70	1481	1658
20	U.C. Energy	none	D	30	80	0	100
21	Green Confl.	AF1800 IF1805 F3150 AF3285	I G C	na	na	0	0
22	San Juan Ag	IF3795	D,G	30	73	405	729
23	San Juan M&I	none	D	30	31	57	30
24	San Juan Energy	none	D	30	20	48	90
25	Paria Confl.	AF38200	I,B	na	na	0	0
26	Lee Ferry	none	F	1	100	8231	8231
27	Lee Ferry Ret.	none	C	na	na	0	0
28	Mead Confl.	IF42949	C,G	na	na	0	0
29	Az/Nv Non-CAP M&I	none	D	50	18	198	384
30	Az/Nv Non-CAP Ag	none	D	50	50	1310	1250
31	CAP	none	D	60	18	765	2100
32	Calif. Ag	none	D	50	50	3902	3903
33	MWD (5)	none	D	50	18	498	498
34	MWD Extra (6)	none	D	80	18	729	729
35	Mexico Delivery	none	D	1	1	1500	1500

1 Priorities for reservoirs are for storage.
2 The gulf demand only exists during the spring season.
3 From Table III-5.
4 I => Inflow G => Gains D => Demand C => Confluence S => Storage B => Bifurcation
5 From Arizona v. California
6 Capacity of MWD system is 1.227 MAF
7 Water volumes in 1000 acre-feet per year.

Table III-4: Seasons

Winter	October...December
Spring	January.....April
Runoff	May.....July
Irrigation	August...September

Table III-5 describes the points where inflow, flow gains, and loss data were available. As is noted in Table III-3, these data were sometimes combined in order to represent the aggregate inflow at a node of the network representation. While the treatment of inflow and flow gains is straightforward, the treatment of losses is not and is described here.

Table III-5: USBR Flow Stations

Station	Type	Description
AF0725	Inflow	AT GLENWOOD SPRINGS, CO ON THE COLORADO RIVER
IF0955	Flow Gains	GAINS ABOVE CAMEO, CO ON THE COLORADO RIVER
AF1246	Inflow	AT BLUE MESA DAM ON THE GUNNISON RIVER
IF1278	Flow Gains	GAINS ABOVE CRYSTAL DAM ON THE GUNNISON RIVER
IF1525	Flow Gains	GAINS ABOVE GRAND JUNCTION ON THE GUNNISON RIVER
AF1800	Inflow	NEAR CISCO, UT ON THE DOLORES RIVER
IF1805	Flow Gains	GAINS ABOVE CISCO, UT ON THE COLORADO RIVER
AF2112	Inflow	AT FONTENELLE DAM ON THE GREEN RIVER
IF2170	Flow Gains	GAINS ABOVE GREEN RIVER, WYO ON THE GREEN RIVER
IF2345	Flow Gains	GAINS ABOVE GREENDALE, UT ON THE GREEN RIVER
AF2510	Inflow	NEAR MAYBELL, COLORADO ON THE YAMPA RIVER
AF2600	Inflow	NEAR LILY, COLORADO ON THE LITTLE SNAKE RIVER
AF3020	Inflow	NEAR RANDLETT, UTAH ON THE DUCHESNE RIVER
AF3065	Inflow	NEAR WATSON, UTAH ON THE WHITE RIVER
IF3150	Flow Gains	GAINS ABOVE GREEN RIVER, UTAH ON THE GREEN RIVER
AF3555	Inflow	NEAR ARCHULETA, NM ON THE SAN JUAN RIVER
IF3795	Flow Gains	GAINS ABOVE BLUFF, UTAH ON THE SAN JUAN RIVER
IF3800	Flow Gains	GAINS ABOVE LEES FERRY, AZ ON THE COLO. RIVER
AF38200	Inflow	PARIA RIVER AT LEES FERRY, ARIZONA
AF3285	Inflow	NEAR GREEN RIVER,UT ON THE SAN RAFAEL
AF40200	Inflow	LITTLE COLORADO RIVER AT CAMERON, ARIZONA
AF40210	Inflow	BLUE SPRINGS (ESTIMATED) NEAR LITTLE COLORADO
AF41500	Inflow	VIRGIN RIVER AT LITTLEFIELD,ARIZONA (MODIFIED
IF42100	Flow Gains	GAINS AT LAKE MEAD ON THE COLORADO RIVER
IF42250	Flow Gains	GAINS AT LAKE MOHAVE ON THE COLORADO RIVER
AF42600	Inflow	BILL WILLIAMS RIVER BELOW ALAMO DAM, ARIZONA
IF42750	Flow Gains	GAINS TO LAKE HAVASU NEAR PARKER DAM, ARIZONA
IF42949	Flow Gains	GAINS ABOVE IMPERIAL DAM, ARIZONA

Flow losses from infiltration and evaporation of course occur in all reaches in the Colorado River System. In most reaches, most of the time, the net of flow gains and losses is positive. However, in some of the lower reaches during periods of low flow, the net is negative. The virgin flow data set used in this study represents net losses as a negative flow gain. MODSIM is not capable of using negative inflows. Thus, it was necessary to modify the program to convert each negative inflow to a demand at the node. This approach has one serious shortcoming--if there is already a demand at the node, the system loss will have the same priority as the demand at the node when in fact the system loss should have the highest priority so that it is satisfied without fail. The nodes where instances of net negative flows occur have been identified (nodes 2, 6, and 28, Table III-3) and system demands have not been placed on them. At these nodes, demand priority is set to one so that channel losses are satisfied when they occur. Note that Table III-3 does not include the demands that represent losses.

The Gila River enters the Colorado River below Imperial Dam. Although the water resources of the Gila River Basin are fully exploited, there are, from time to time, flows in this tributary which would be credited to deliveries under the Mexican Treaty. These flows are rare and will generally occur during periods of abundant flow when excess flows on the mainstem are sufficient to meet treaty requirements. For these reasons, Gila River flows were not included in this analysis.

Return flows from the Wellton-Mohawk Irrigation District flow through Mexico to the Santa Clara Slough. Currently, these flows are not credited to the treaty delivery obligation due to their low quality. Upon completion of desalination plants to upgrade the quality of these waters, they would become

creditable toward the delivery obligation. In this analysis, these return flows were not credited toward the treaty delivery obligation. Furthermore, Imperial Valley return flows, which go to Mexico, have been ignored.

There are seven reservoirs represented in the model network. These are described in Table III-6. Generally, these reservoirs represent directly the active capacity of a real reservoir of the same name. There are two exceptions: In the model, the conservation pool (as opposed to the flood control pool) of Lake Mead has been consolidated with the capacity of Lake Havasu and Lake Mojave. These reservoirs are operated as one. The total capacity of the seven reservoirs, including the Mead flood pool, is 62,489,000 acre-feet. The reservoirs were assumed to be full at the start of each simulation.

Table III-6: Reservoirs

Name	Node	Capacity	Dead Storage	Assumed Starting Contents
Fontenelle	1	345	195	345
Flaming Gorge	2	3789	40	3789
Curecanti	3	1058	111	1058
Navaho	4	1709	13	1709
Powell	5	27000	1998	27000
Mead Conservation	6	23088	0	23088
Mead Flood Pool (1)	7	5500	0	5350
Total		62,489		

1 USCOE, USBR, 1982.

The flood pool of Lake Mead has been separated from the conservation pool to allow realistic modelling of the rules used by the Interior Department to operate Lake Mead for flood protection. This is described in somewhat more detail under the constrained case.

Reservoir evaporation is applied at the end of each season. The area/volume relationship for a reservoir is specified at several points. The evaporation rate is specified in the surface area/volume table for each period. Surface area is determined by linear interpolation; evaporation is the product of the area and the seasonal rate. Area/volume relationships and evaporation rates were adopted from the USBR Colorado River Simulation System (USBR, CRSS, 1982).

3. Representation of Upper Colorado River water use

DWDSYM explicitly estimates the maximum firm yield of Denver's water supply system while operating the Colorado River mainstem in Colorado on a call basis. Denver's existing system and various future system configurations can be modeled. Alternate configurations can include both physical changes in Denver's system and institutional changes concerning the operation of the river. In addition, the demands of the Colorado-Big Thompson project and water sales from Green Mountain reservoir can be specified.

The model utilizes a number of virgin flow data files for several West Slope river reaches to represent the operation of the Colorado River above Glenwood Springs. In order to model the effects of increased runoff, a number of virgin flow files were modified to reflect the flow increases expected from a representative vegetation manipulation program in the Arapaho National Forest. Specifically, the virgin flows of the various tributaries of the Fraser, Williams Fork, and the Colorado River above Kremmling and the Colorado River at Dotsero were adjusted to reflect increased flows from vegetative manipulation in the months of April, May, and June (Table III-1). DWDSYM was then used to determine Denver's system yields under normal and enhanced virgin flows for Denver's existing system and for future configurations of the system as

currently planned by Denver. In addition, the water demands associated with the Colorado-Big Thompson project and West Slope use of Green Mountain Reservoir were tested under existing and future levels. The results allowed evaluation of effects on Denver's system yield and on potential water availability from the Colorado-Big Thompson project and from Green Mountain Reservoir for use within the Colorado River Basin. While there are other diversions in the sub-basin which could benefit from increased runoff, such as the Windy Gap and Homestake projects, it was felt that representative results could be obtained from examination of the demands of Denver and Green Mountain reservoir.

D. Data

1. Hydrologic data base

Reconstructed historic virgin flow was used as the basis for the hydrologic modeling because consumption from the Colorado River has been increasing over the historical period, and because the scope of the project did not allow for development of synthetic traces. The flow data used were developed by the U.S. Bureau of Reclamation for use with the Colorado River Simulation Model (USBR, CRSM, 1983).

The raw data contain monthly values for 28 stations throughout the Colorado River Basin (see Table III-5). The data are complete for all stations over the period 1906..1977 so this period was selected to use for modeling.

It is worth noting that the hydrologic record on the Colorado River is short. Generally, accurate flows are not available prior to 1906, although some data are available from as early as 1896. During the period from roughly 1903 through 1930 the Colorado river experienced very high flows. Examination of tree rings indicate that these flows may represent the wettest period in the last 600 years (Stockton and Jacoby, 1976).

Because of the peculiar shape of the hydrologic record for the Colorado River, the ideal approach would be to derive statistics from the historic flow records and, to the extent possible, the tree ring data, and use these statistics to develop synthetic traces to be used as the basis for the analysis. However, the scope of the study would not allow for such an undertaking. In addition, the USBR flow and consumption data used here have become to some degree a de facto standard. For this reason, use of these data will allow direct comparison of the results of this study with those of others.

It was necessary to consolidate data to conform to the nodes and seasons used in the model. Further, it was necessary to modify the data to reflect the enhancement from vegetative manipulation. This was done as follows: The 28 data stations were mapped into 13 nodes for modeling purposes (see Table III-3). Flow enhancement occurred at the Glenwood Springs station which was mapped into node 18.

2. Water uses and losses

Because the model studies were based on virgin flows, it was necessary to quantify the present level (1980) of consumption as well as additional consumption which could occur in the future. Because in the unconstrained case it would be possible for a potential use to displace current consumption, it was necessary that the current uses as well as prospective uses be classifed according to category and net value.

Consumption was the measure of use. Although the use of consumption could mask some local shortages, it was impractical to explicitly represent the diversion and return flow of each of the thousands of diversions in the Upper Basin.

The bases for the water use figures used herein were developed by the US Bureau of Reclamation for use as input to the Colorado River Simulation Model (CRSM) for the purpose of modeling salinity in the basin (USBR, 1983). These data are listed in the Appendix.

In the Upper Basin, uses were aggregated into groups of similar type which had roughly similar net value. The classes of use were Agriculture, Municipal and Industrial (M&I), and Energy. This aggregation was made principally to facilitate the unconstrained analysis where uses would be assigned a rank based on their net value. The same groupings were used for the constrained case.

Uses in the Upper Basin were also aggregated by water use areas. One of the basic assumptions of the study was that all existing uses of a class in the Upper Basin have the same net value. Based on this assumption, it would be necessary only to provide a node for each class of use. However, to do so could introduce errors by concealing shortages at higher stations by assuming that such aggregated demands could be met with the aggregate inflows, some of which are not physically accessible by all of the demands. Because of the limited scope of this project, it was impossible to model each use. Rather, uses were aggregated within sub-basins to minimize errors.

The water use areas in the Upper Basin were: the upper Green River above Flaming Gorge Reservoir; the Yampa/White/Little Snake drainage; the Upper Colorado including the Colorado and Gunnison Rivers above and including Grand Junction, Colorado and the Dolores drainage; the San Juan drainage; and western tributaries in Utah such as the Duchesne.

In the Lower Basin, small uses were aggregated in the Upper Basin. However, most uses in the Lower Basin are served by large diversions which provide water to a single class of users. In the constrained case, these diversions have different priorities. Thus, it was necessary to provide a separate node for each of the large Lower Basin diversions. With the exception of node 8, M&I and energy demands were assumed to be equal across months. Agricultural demands were allocated, based on Bureau of Reclamation data, as 10, 10, 20, and 60% in the Upper Basin and 20, 20, 20, and 40% in the Lower Basin, to the winter, spring, runoff, and irrigation seasons, respectiely.

Two water use scenarios were developed based on consumption at the current time and at ultimate development. Table III-3 displays the complete water demand (labeled "consumption" in Table III-3) data set used for each of the scenarios.

3. Priorities and Operation - constrained case

The Upper Basin Reservoirs were filled after any demand in the Upper Basin (including the Lee Ferry delivery obligation) but before any demand or reservoir in the Lower Basin.

The Lake Mead (et al) conservation pool was filled after all demands (excepting the MWD excess demands) in the Lower Basin were satisfied. Most Lower Basin demand could be satisfied from storage in Lake Mead. The single exception was California's excess diversion (above the 4.4 MAF allocated to that state by the decision in Arizona v. California).

All beneficial consumptive uses in the Upper Basin were given identical priorities. So long as all demands are met, there is no need to differentiate among users. In the case of shortage, recognizing that the purpose of the study

was to dentify the type of use to which enhanced flows were put rather than the particular user, water was allocated to uses proportional to demand. The validity of this method is based on the assumption that the mix of uses at the priority margin is similar to the average.

Upper Basin demands were satisfied before any system reservoirs and Lower Basin demands, but were subordinate to the Lee Ferry delivery obligation.

Demands in the Lower Basin were given priorities which reflect the U.S. Supreme Court decision in Arizona v. California (1968). California's 4.4 MAF of high-priority consumption and Arizona's non-CAP consumption were satisfied first. CAP was satisfied next, and California's "excess" consumption (above the 4.4 MAF level) was satisfied last. If there was excess water supply to the Lower Basin (if the Mead flood control pool was not empty), then the excess California uses were satisfied. Note that the Secretary of the Interior has the authority to declare a surplus at Lake Mead which allows the MWD excess demand to be satisfied from the Mead Conservation pool. This was not simulated in the model.

Nodes 29 and 30 (see Table III-3) represent M&I and agricultural demands respectively, located along the Colorado River in Arizona and Nevada. Node 31 represents both agricultural and M&I uses supplied by the CAP. Node 32 represents California agricultural uses (largely Imperial Valley, but also along the main stem). Node 33 represents the Los Angeles Metropolitan Water District demands. Demands at Nodes 32 and 33 total to 4.4. MAF, California's high-priority entitlement as set by Arizona v. California -- Node 34 represents demands in the metropolitan Los Angeles area which are in excess of the high-priority entitlement. These demands have the lowest priority in the Lower

Basin. The demand level at Node 34, 729,000 acre feet, was determined by taking the difference between the highest historic delivery by MWD and its high-priority entitlement (498,000 acre-feet, Node 33).

Similarly, the ultimate demand of CAP was set at the physical capacity of the diversion. Strictly speaking, this overstates Arizona's entitlement in the constrained case (Arizona's total entitlement, as set by Arizona v. California is 2.8 MAF).

When simulating operation of the system under institutional constraints, the Lee Ferry delivery obligation served to separate the system into the Upper Basin and the Lower Basin. Under Article III(c) of the 1922 Compact, the Upper Basin must allow 75,000,000 acre-feet to flow past the Lee Ferry gage in any ten-year period. One common interpretation of Article III(c) of the 1922 Compact, however, holds that the Upper Basin must also contribute half of the 1.5 MAF/year delivery obligation to Mexico for a total obligation of 82.5 MAF in any ten-year period.

The current operating rules of the Department of the Interior for Glen Canyon Dam both reflect and disclaim this interpretation. These rules provide for a minimum release from Glen Canyon Dam of 8.23 MAF per year. The Paria River confluence with the Mainstem is below Glen Canyon Dam (and the Lee's Ferry gage) but above the Compact Point at Lee Ferry. The Paria contributes an average of 20,000 acre-feet to bring the total annual delivery to 8.25 MAF on the average. The rules do not provide any mechanism whereby releases from Glen Canyon Dam may be reduced below 8.23 MAF. Thus, the rules do not implement the strict interpretation of the 1922 Compact which would cause the release at Glen Canyon to be reduced below 8.23 MAF to reflect higher releases during the previous ten years.

In the basin-wide model, the Lee Ferry obligation was set at 8.23 MAF and satisfied before any demand or storage in the Upper Basin.

The Department of the Interior, through the U.S Corps of Engineers, is required to operate Lake Mead to certain criteria in order to provide a measure of flood protection to downstream areas. These criteria are set out in the field working agreement between the Corps of Engineers and the Bureau of Reclamation (USCOE, USBR, 1982). They specify that a flood pool of a minimum of 5.35 MAF be available in Lake Mead on January 1 of each year. In order to simulate the evacuation which must occur, it was necessary for a separate flood control reservoir to be created. This reservoir, called the Mead Flood Control Reservoir, was filled, during the Spring Runoff, Irrigation, and Winter Seasons, after any other reservoir or demand in the Lower Basin

To simulate the flood control evacuation, a demand was invoked at the Gulf of California which was larger than the sum of any inflow which could occur at Lee Ferry plus the capacity of the flood control reservoir. This demand operated only during the winter season (which ends on December 31) and was subordinate to all other system reservoirs and demands except the flood control reservoir (see Table III-3). The result was that the flood control space was evacuated on January 1, if not by useful consumptive demands, then by the flood control demand.

A delivery of 1.5 MAF from node 35 was satisfied before all basin demands or storage.

The Upper Basin demands total 3.454 and 5.527 MAF in the current and full development (ultimate) scenarios. The two corresponding Lower Basin demands total 7.402 and 8.864 MAF. Adding in the 1.5 MAF Mexico delivery yields total demands of 12.356 and 15.611 MAF for the current and ultimate scenarios, respectively.

4. Priorities and Operation - unconstrained case

In the unconstrained case, water was allocated among uses according to the net value of water accruing to that use. Storage was maximized at the end of each season after all demands were satisfied. It was assumed that no delivery obligation was in effect at Lee Ferry and that all releases from Glen Canyon were made only to satisfy Lower Basin demands and the Mexico delivery obligation.

Demands throughout the entire basin, with the exception of the Mexico delivery, were given priorities which reflected their net economic value and were mapped into the range 10-80 (Table III-3). Note that CAP water in this case was assumed to go entirely to M&I uses.

Table III-7 summarizes the basis for the priorities given to water use in the unconstrained case. The marginal economic value of water in each type of use at each location was adopted from an earlier publication (Krutilla, Bowes and Sherman, 1983), and is shown in the third column of Table III-7.

Water will generally be supplied to a given node by implementing a series of projects. A unit cost was determined for each necessary project . For federal projects (USBR), agency budget requests (form PF-65) and project data sheets were used where available. For other projects, a variety of sources were

used, including submissions necessary to comply with federal licensing requirements or the National Environmental Policy Act of 1969. Otherwise, costs were estimated using best professional judgement. For each project, a net value of produced water was calculated from the gross marginal value, amortized capital costs and operating costs.

Table III-7
Water-Use Priorities and Basis Costs and Values (Dollars/Acre-foot)

Node	Name	Marginal Value	Net Value	Rank
9	Upper Green Ag	10	10	70
10	U.G. M&I	60	54	26
11	U.G. Energy	60	0	80
12	Yampa/White Ag	10	10	70
13	Yampa/White M&I	60	60	20
14	Yampa/White Energy	60	48	32
15	West Utah Ag	10	9	71
16	West Utah M&I	60	59	21
17	West Utah Energy	60	4	76
18	Upper Colo. Ag	10	10	70
19	U.C. M&I	60	60	20
20	U.C. Energy	60	0	80
22	San Juan Ag	10	7	73
23	San Juan M&I	60	49	31
24	San Juan Energy	60	60	20
29	Az/Nv Non-CAP M&I	112	62	18
30	Az/Nv Non-CAP Ag	30	30	50
31	CAP	112	62	18
32	Calif. Ag	30	30	50
33	MWD 5	112	62	18
34	MWD Extra 6	112	62	18

For each node, the average net unit value was calculated as the weighted average of net unit values for all projects. These data are shown in the fourth column of Table III-7. Each such value was then transformed into an objective function weight by preserving ranking of those values (a high net value implies a high water allocation priority, which is expressed by a low number). The resulting objective function weights are shown in the fifth column of Table III-7 and as the unconstrained rank in Table III-3.

Water use priorities were restricted to the range 10-80. Values lower than 80 were used for channel losses and the Lee Ferry delivery obligation. Reservoirs were given priorities in the range 81-97. Note that reservoir priority was generally decreased with elevation in the basin. This was to insure that water was stored as high as possible in order to minimize evaporative losses.

The flood control evacuation was disabled by setting the evacuation demand to zero.

IV. SCENARIOS - DESCRIPTIONS AND RESULTS

A. Interstate Water Use Changes

1. Effects of runoff increases given current institutions and demands

The MODSIM network optimization model was specified for the Colorado River system, as described previously, and then a series of computer runs was performed in which the parameters of inflow, demand, and water-use priorities were varied systematically. The first of those runs represented the baseline case, i.e., a situation characterized by no vegetation manipulation, climatic conditions equal to a repeat of the 1906-1977 period of record, water demands and storage facilities representative of 1980, and current interstate and intrastate water allocation institutions remaining unmodified. Then, a second run was performed in which the only change from the baseline assumptions was that of vegetation manipulation on the Arapahoe National Forest, and consequent increased flows into the Colorado River.

As shown in the first two columns of Table IV-1, the streamflow augmentation from vegetation manipulation produced almost no change in water consumption anywhere in the Colorado River system under the assumptions of the baseline scenario. In other words, the increased flows went largely unused, in the sense of the uses which were modeled (instream uses such as hydroelectric power generation, salinity control, fishery habitat maintenance, and water-based recreation would have been affected). This result is due to the fact that there were no physically satisfiable yet unsatisfied demands in the Upper Basin, and the flows were stored in Lake Powell and not released for Lower Basin use except in years of high run-off, at which times Lower Basin demands were already fully met. In such years, if storage space existed in Lake Mead, increased flows would be stored therein, subject to downstream demands, but usually would be

released thereafter to meet the flood control objective. The increased flows, which averaged about 82,000 acre-feet annually, largely flowed across the international boundary into Mexico, although a small percentage evaporated and even smaller amounts were consumed in the Lower Basin (6,000 acre-feet/year at node 34) or stored in system reservoirs. This finding served as a prelude to subsequent runs, in which several parameters were varied in an attempt to determine the sensitivity of the non-use conclusion to potential changes in future conditions. Although the potential for use of increased flows was the primary focus of these subsequent explorations, it was not the only conclusion of interest. As it turned out, other findings emerged which were more significant. They are reported as well.

Table IV-1. Projected Average Annual Colorado River Water Disposition, Current 1980 Demand Conditions (Thousands of Acre Feet)

	With Existing Interstate Water Allocation Institutions		Without Existing Interstate Water Allocation Institutions	
	Natural Flows Only	Flows Augmented by Vegetation Manipulation	Natural Flows Only	Flows Augmented by Vegetation Manipulation
Upper Basin				
Consumptive Use	3451	3451	3451	3451
Evaporation	752	753	782	782
Shortages	3	3	3	3
Lower Basin				
Consumptive Use	7189	7195	7398	7398
Evaporation	1475	1484	1524	1545
Shortages	209	203	0	0
Net Change in Reservoir Contents	-240	-238	-197	-195
Outflow to Mexico	3536	3600	3205	3263

2. Effects of increased water demands given current institutions

The initial conclusion that flow augmentation produces little change in beneficial water use under current demand conditions immediately raised the question of how that conclusion might change if proposed development projects were to be built, thereby increasing the physical capability to satisfy additional water demands. Water demands projected for the full development scenarios were about 30 percent above those of the current scenario. As shown in Table IV-2, the conclusion is not greatly changed under the full development scenario.

Average annual Upper Basin shortages were only about 18,000 acre-feet annually under the full development scenario and were unaffected by increased flows. These shortages are "local" ones, which is to say that they occur at high elevations where they cannot be alleviated by the operation of existing or planned storage and diversion facilities. They are not limitations imposed by the water allocations assigned to the Upper Division states under the Colorado River Compacts, because under the simulated conditions, there were no shortages in the Lee Ferry delivery, so no curtailment of Upper Basin uses was necessary.

Lower Division shortages in the full development scenario are substantial. Under baseline runoff conditions they amount to an average of 644,000 acre-feet annually (nearly eight percent of total Lower Division Colorado River water demand). Nearly ninety percent of the shortages are reductions in deliveries to the Metropolitan Water District of Southern California, nearly half of total Colorado River water demand by the district, which currently uses more than its allotted share because neither CAP nor the Upper Basin are yet able to use their full allocations.

Table IV-2. Projected Average Annual Colorado River Water Disposition, Full Development Conditions (Thousands of Acre Feet)

	With Existing Interstate Water Allocation Institutions		Without Existing Interstate Water Allocation Institutions	
	Natural Flows Only	Flows Augmented by Vegetation Manipulation	Natural Flows Only	Flows Augmented by Vegetation Manipulation
Upper Basin				
Consumptive Use	5244	5244	5104	5126
Evaporation	631	640	614	621
Shortages	18	18	158	136
Lower Basin				
Consumptive Use	8220	8236	8755	8771
Evaporation	755	766	656	668
Shortages	644	628	109	93
Net Change in Reservoir Contents	-757	-737	-833	-833
Outflow to Mexico	2071	2095	1869	1894

Shortages would have been greater without average annual net withdrawals from storage of 757,000 acre-feet per year. Over the 72-year record this totals 54 MAF, representing 87 percent of total storage capacity. This stored water was used to supply deficits during the longer than 50-year, unbounded critical period represented by the data. Shortages began to occur near the end of the historic trace.

The effects of enhancing Colorado River flows through vegetation manipulation in the full development scenario also are shown in Table IV-2. In summary, these effects were to reduce Lower Division shortages by about 16,000 acre-feet annually, to increase total evaporation by 20,000 acre-feet, and to increase reservoir storage and outflow to Mexico by approximately 20,000 and 24,000 acre-feet, respectively. When compared with the current demand scenario,

twice as much of the additional runoff evaporates and a nearly equivalent drop in outflow to Mexico occurs. In short, the runoff increases which could be produced by vegetation manipulation in the Arapaho National Forest would not relieve water shortages nor increase water use under existing institutional arrangements, except in the Lower Division under maximum water demand assumptions. Virtually all of the increased runoff would flow across the international border or would be evaporated or stored (which storage would later be divided among outflow, evaporation, and consumptive use in probably much the same ratios).

3. Effects of Institutional Change

The scenarios which included the assumption of no change in the institutional arrangements for interstate allocation of Colorado River water included both a set of priorities among virtual diversion points (objective function weights) and a set of final demands for water which were consistent with those institutional arrangements. The assumption of unchanged institutional arrangements was removed by reordering priorities among virtual diversion points to correspond with the approximate market prices for water for those uses at those points. Projected demands for water were not altered in the current or full development scenarios.

The effects of removing the institutional constraints under current demand conditions are shown in Table IV-1. In part, (with natural flows) they were to increase average demand evaporation by 79,000 acre-feet, to decrease average annual outflow to Mexico by 331,000 acre-feet, and to decrease the annual drop in reservoir contents by 43,000 acre-feet. These changes are attributable to removal of the flood control operation rules at Lake Mead, and the subordination of storage to the California "excess" use. Higher levels at Lake Mead caused

evaporation to increase. Without flood control evacuations, outflows to Mexico decreased while net reservoir contents increased. The most important change was to reduce MWD shortages by 209,000 acre-feet annually.

Shortages were more widespread under the full development conditions (Table IV-2). The effects of removing institutional constraints were to decrease average annual evaporation by 116,000 acre-feet, to decrease average annual outflows by 202,000 acre-feet (outflows are still in excess of treaty obligations), to increase the average annual drop in reservoir contents by 76,000 acre-feet, and to reduce projected average annual Lower Division shortages from 644,000 to 109,000 acre-feet. Notably, this 535,000 acre-foot reduction in Lower Division shortages came at the expense of an increase of only 140,000 acre-feet in Upper Division shortages, which reflects the consequences of more efficient system operation and resultant decreased outflows and evaporation.

These changes were largely due to elimination of the consideration of compacts and court decisions which cause the Secretary of the Interior to store water in Lake Powell rather than release it to meet excess California demands. This stored water is then available to meet delivery obligations to the Lower Basin in the event of increased Upper Basin usage or low run-off conditions, one aspect of existing institutional arrangements. A result is an increase in overall net withdrawal from storage . This increase amounted to some 60 MAF over the study period.

B. Water Use Changes Within Colorado

The DWDSYM analysis showed that increased flows from vegetation manipulation in the Arapaho National Forest would primarily benefit transmountain water users whose diversion/storage facilities could directly intercept such flows, namely the Denver water supply system, the Colorado-Big Thompson, and Windy Gap projects. Other water users within the sub-basin would benefit only minimally from a slight lessening of local calls.

Under the flow enhancements, of Table III-2 the yields of the Denver water supply system, the Colorado-Big Thompson project, and the Windy Gap Project could increase by the amounts shown in Table IV-3.

Table IV-3. Increased Yields in Colorado Due to Vegetation Manipulation

Project	Amount of Increase (acre-feet)
Existing Denver System	7,000
Denver Expansions	1,000
Colorado-Big Thompson	9,000
Windy Gap	3,000

Under current demand conditions, these increased yields would not be utilized, as all existing water demands are being met. Even under future demand conditions, no shrotages are projected to exist; the increased yields listed above would serve to postpone or replace portions of other projects currently planned for construction.

V. SUMMARY AND CONCLUSIONS

The primary objective of this study was to project the probable future uses of additional flows in the Colorado River due to vegetation manipulation in the river's headwater area. Consequently, the most obvious parameter to be varied was river flow. However, additional parameters were also of interest, initially because it was thought that the uses made of increased run-off might vary as water demands grew over time and with differences in such factors as climate and the institutions which govern water allocation.

A. Hydrologic Aspects

The anticipated runoff increase for climatic conditions equal to those in each of the years for which records were available varies from 49,000 acre-feet to 106,000 acre-feet, with a mean of 82,000 acre-feet. The increase in each year is distributed over the period April 15 to June 15.

The effects of enhancing streamflows through vegetation manipulation are summarized in Table V-1. Under existing institutional arrangements, and under current demand conditions, they were to increase outflow (over 80 percent of the increase flowed unused into Mexico), to increase evaporation modestly, and to alleviate Lower Basin shortages and increase storage slightly. Under full development conditions, the increased flows were more evenly divided between outflow, evaporation, storage, and (to a lesser extent) alleviating Lower Basin shortages. Removing institutional constraints did change this conclusion. Enhanced flows continued to be almost entirely undiverted under current demand conditions. Under full development conditions, however, increased flows were distributed roughly equally between evaporation, outflow, and alleviation of shortages in the Upper and Lower Basins, respectively. Under these

circumstances, nearly half of the increased flows would be utilized to alleviate shortage throughout the entire Colorado River Basin. It is noteworthy that under full development conditions, the removal of institutional constraints causes the utilization rate of increased flows to rise from 20 percent to 48 percent.

Table V-1. Disposition of Increased Flows Due to Vegetation Manipulation (Thousands of Acre Feet Annually)

With Existing Interstate Water Allocation Institutions

Demand Conditions	Evaporation	Storage	Outflow	Alleviation of Lower Basin Shortages	Alleviation of Upper Basin Shortages
Current	10	2	64	6	0
Full development	20	20	24	16	0

Without Existing Interstate Water Allocation Institutions

Demand Conditions	Evaporation	Storage	Outflow	Alleviation of Lower Basin Shortages	Alleviation of Upper Basin Shortages
Current	21	2	58	0	0
Full development	19	0	25	16	22

The Colorado River Basin is characterized by substantial annual variation in precipitation and runoff, and doubtless by substantial longer term variation as well. This variation can be expected to cause variability in the potential additional runoff produced by vegetation manipulation, as discussed in the preceding section, and also in total runoff throughout the basin. Ideally, one would use available data on historic runoff in the basin as a sample from which to infer possible future runoff patterns and then investigate the implications for the uses of augmented flows of selected potential runoff patterns. Such a

procedure would rely on statistical analysis of historical data, and was deemed both too costly and unnecessary for this initial reconnaissance investigation. Instead, virtual virgin flows data were obtained from the Bureau of Reclamation for the 72-year period for which they were available (1906 through 1977). These data were based upon stream gage readings, which were then adjusted for estimated withdrawals, return flows, reservoir evaporation, and channel losses, all of which are known only imperfectly.

B. Economic Aspects

The initial plan was to investigate the likely uses of increased flows for probable levels of water demand in the years 1985 and 1995. However, the states of the Upper Division are currently using far less than their entitlements under the Colorado River Compacts and it is impossible for them to create by 1995 the additional reservoir storage which would be necessary to permit the diversion and use of their full entitlements, whether or not the economic demand for that water had materialized by that time. As a result, the institutional arrangements which govern the allocation if Colorado River water between the Upper Division and the Lower Division, and between the several states of the Upper Division, would not be invoked during this time period, as they have not been invoked in the past. Consequently, it seemed advisable to project demands well beyond 1995, in order to investigate how the existing institutional arrangements might affect the use of increased flows. Two scenarios, the first based on current development and demand conditions and the second based upon full development, as exemplified by planned projects, were ultimately selected for the analysis.

Table V-2 summarizes shortages in the Upper Basin and Lower Basin under water demands which characterize the so-called current and full development scenarios under existing institutions (Case 1,A and B). They differ with

respect to the water storage and delivery projects assumed to be in place. In each case, effective demand is assumed to exist for all of the water which the included projects are capable of delivering.

Table V-2 also shows for each case the projected effects of those demands upon Colorado River water use under the two assumptions regarding runoff. It reveals that the prospect of Upper Basin water shortages is remote, which may be a consolation to present Upper Basin water users but a source of alarm to those who fear that Upper Basin water entitlements may be lost if they are not soon perfected. It also reveals that prospective Lower Basin shortages will be substantial.

C. Institutional Aspects

One of the objectives of the study was to estimate the potential effects of changes in institutional arrangements upon the use of increased flows, inasmuch as institutional change is an ever-present fact of life, and may be particularly important in the near future as competition for limited water supplies increases in the Colorado River Basin.

Two different sets of institutions influence water use in the basin. The first set consists of the international treaty, the two Colorado River interstate compacts, court decisions such as Arizona v. California, and the operating rules for the major water regulation and storage projects of the Bureau of Reclamation. These institutions, which are often referred to collectively as the "law of the river," shape the pattern of interstate water allocation. The interstate compacts have yet to come into use, because the states of the Upper Division have never made full use of their compact

Table V-2. Projected Average Annual Colorado River Water Use Under Alternative Demand Conditions (Thousands of Acre-Feet)

Case 1: With Existing Institutions

	(A) Current Demands Shortages			(B) Full Development Shortages	
	Demand	Natural Flows	Enhanced Flows	Demand	Natural Flows	Enhanced Flows
Upper Basin						
Agriculture	2890	2	2	3687	6	6
M & I	449	0	0	968	2	2
Energy	113	0	0	605	10	10
Lower Basin						
Non-CAP Ag	5211	0	0	5154	17	14
CAP	764	0	0	2100	75	65
California M&I(1)	1226	309(2)	305(2)	1226	592(2)	591(2)
NV and Non-CAP M & I	305	0	0	492	0	0

1. MWD total, including excess.
2. Shortage occurs in excess deliveries.

Case 2: Without Existing Institutions

	(A) Current Demands Shortages			(B) Full Development Shortages	
	Demand	Natural Flows	Enhanced Flows	Demand	Natural Flows	Enhanced Flows
Upper Basin						
Agriculture	2890	3	3	3687	114	95
M & I	449	0	0	968	11	11
Energy	113	0	0	605	32	31
Lower Basin						
Non-CAP Ag	5211	0	0	5154	114	88
CAP	764	0	0	2100	0	0
California M&I	1226	0	0	1226	5	3
NV and Non-CAP M & I	305	0	0	492	0	0

entitlements, under any interpretation of the compacts, and thus there has been no need to deal with the question of shortage. However, competition within the Lower Division is now appearing with the completion of the Central Arizona Project, and California is being forced to reduce its excess diversions, under the terms of Arizona v. California. Furthermore, there is great concern in all

of the Colorado Basin states with respect to how the law of the river will be interpreted, how it will be implemented, and whether and how it will be modified in the future.

Water allocation within each of the Colorado Basin states generally occurs pursuant to the doctrine of prior appropriation, as that doctrine is implemented and embellished by the laws of each state. Federal and Indian reserved water rights must be respected, as well, but the quantification of those reserved rights, many of which are very senior, has barely begun. Furthermore, increasing competition for limited water supplies creates pressure for institutional change in order to facilitate transfers of water to the more productive uses, and to increase the efficiency of use in all applications.

In the light of these considerations, it seemed wise to include investigations of the sensitivity of the primary research results (projected patterns of use of increased flows) to possible changes in both interstate and intrastate water allocation institutions. This was done first by modeling the effects of the existing interstate water allocation institutions (the law of the river) as a set of priorities for water uses at each of the virtual diversion points in the system. Then, the model was respecified using priorities which corresponded to the marginal value of water in each of the identified uses, in order to estimate the water use pattern which might be expected to emerge if the law of the river were to be abandoned and free exchanges of water were to be permitted between states, and if those free exchanges operated to transfer water as market prices might dictate.

The marginal value of water is highest in municipal and industrial water uses, in both the Upper and Lower Basins. It is lowest in agricultural (irrigation) uses in both basins. Furthermore, the marginal values of water

uses in the Lower Basin are higher than those of similar uses in the Upper Basin. This is true both because competition for water is greater in the Lower Basin and because Lower Basin agriculture is more productive than it is at higher elevations in the Upper Basin. Market forces, therefore, will favor the Lower Basin over the Upper Basin and, within each basin, will favor municipal and industrial water uses over irrigation.

As discussed previously, the projected effects upon the use of increased Colorado River flows of removing the existing structure of interstate water allocation institutions (the law of the river) were minor, except under assumed major demand increases in both the Upper and Lower Basins. However, the projected effects of this radical institutional change upon overall Colorado River water use were more interesting. Table V-2, Case 2, shows the effect of enhanced flows under the unconstrained institutional setting. Table V-4 shows the net change in water use attributable to institutional change.

Under present demand conditions, the effect is one of eliminating a substantial share of Lower Basin water shortages while increasing evaporation and channel losses and decreasing outflows to Mexico. Under the higher demands which characterize the full development scenario, however, an even larger reduction in shortages occurs as a result of institutional change. Major Lower Basin shortages are eliminated at the cost of much smaller shortages in Upper Basin water use. The full development scenario is characterized by a 52 percent increase in Upper Basin water demands over current levels and a 20 percent increase in Lower Basin demands.

Under these circumstances, the removal of institutional constraints on interstate transfers of water produces an alleviation of Lower Basin shortages of 535 thousand acre-feet at the cost of increasing Upper Basin shortages by

about one-fourth that magnitude (140 thousand acre-feet), on the average. A substantial reduction in outflows to Mexico also occurs, although Mexico still receives about 20 percent more than her treaty entitlement (in the form of infrequent spring flood flows). Evaporation losses are reduced to a modest level and reservoir conservation storage declines to zero at the end of the period.

While the increase in Upper Basin shortages is an obvious and necessary consequence of unfilled demand and higher water values in the Lower Basin, the finding that those shortages are so much smaller than the resulting increases in higher-valued Lower Basin uses is surprising. It indicates that the economic opportunity costs of existing water allocation institutions may be even higher than has generally been supposed, and that the potential gains which could be produced by institutional innovation, should they be appropriately distributed, may be great enough to create the incentives to accomplish such changes. This is an interesting hypothesis for further research, and may be the most significant finding of this study.

Table V-4. Projected Average Annual Changes in Colorado River Water Use Produced by Abandoning Existing Interstate Water Allocation Institutions (Thousands of Acre-Feet)

	Demand Condition	
	Current	Full Development
Upper Basin Shortages	0	140
Lower Basin Shortages	-209	-535
Evaporation and Channel Losses	+79	-116
Reservoir Storage	+43	-76
Outflow to Mexico	-331	-202

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APPENDIX A

WATER DEVELOPMENT PROJECTS PROPOSED FOR THE COLORADO RIVER BASIN

(USBR, 1985)

Table A
CRSS projected depletions
(Unit--1,000 acre-feet/year)

Upper Basin projects	1983	1990	2000	2010
Arizona				
Comprehensive Framework Study	10	10	10	10
Miscellaneous additional depletions				
Irrigation	2	2	2	2
Municipal and domestic	1	4	4	4
Navajo Powerplant	21	34	34	34
Gallup-Navajo Indian				
Water Supply Project (temporary)	0	(5)	(7)	(7)
Total depletions	34	50	50	50
Compact apportionment	50	50	50	50
Remaining water available	16	0	0	0
Wyoming				
Comprehensive Framework Study	282	282	282	282
Miscellaneous additional depletions				
Irrigation and livestock	6	17	27	35
Municipal	3	5	8	11
Reclamation projects				
Seedskadee	6	20	20	20
Lyman	10	10	10	10
Savery-Pot Hook	0	0	0	0
La Barge	0	0	0	0
Transmountain diversions	8	8	28	50
Industrial uses[1/]				180
Thermal electric	29	54	76	
Mineral	24	34	50	
Coal gasification	0	0	10	
Oil shale	0	0	3	
Total depletions	368	430	514	588
Evaporation, storage units	73	73	73	73
Total	441	503	587	661
State share of 5.8 million acre-foot yield	805	805	805	805
Remaining water available	364	302	218	144
Colorado				
Comprehensive Framework Study	1,707	1,707	1,707	1,707
Miscellaneous additional depletions				
Irrigation	24	24	24	24
Municipal and industrial	5	6	7	10
Fish and wildlife	1	1	1	1
Minerals	1	1	1	1
Exports				
Denver Expansion	48	70	100	130
Homestake Expansion	28	48	48	48
Independence Pass Expansion	7	7	7	7
Pueblo Expansion	3	3	3	3
Colorado Springs Expansion	0	0	5	5
Englewood	10	10	10	10
Fryingpan-Arkansas	69	69	69	69
Windy Gap	0	54	54	54
Reclamation projects				
Animas-La Plata	0	0	121	121
Bostwick Park	4	4	4	4
Dallas Creek	0	11	13	17
Dolores	0	61	81	81
Fruitland Mesa	0	0	0	0
San Miguel	0	0	0	0
Savery-Pot Hook	0	0	0	0
Upper Gunnison River Basin	0	5	10	15
West Divide	0	0	0	0
Municipal, industrial, and domestic				
Taylor Draw Reservoir	0	2	6	7
Stagecoach Project	0	2	4	4
Ruedi contracts	0	16	49	49
Blue Mesa contracts	0	10	10	10
Oil shale	0	2	8	42
Thermal-electric powerplants				
Craig-Hayden	13	18	18	18
Colorado Ute-Southwest Project	0	0	5	5
Total depletions	1,920	2,131	2,365	2,442
Evaporation, storage units	269	269	269	269
Total	2,189	2,400	2,634	2,711
State share of 5.8 million acre-foot yield	2,976	2,976	2,976	2,976
Remaining water available	787	576	342	265

1/ 2010 types of uses were not itemized.

Table A
CRSS projected depletions
(Unit--1,000 acre-feet/year)

Upper Basin projects	1983	1990	2000	2010
New Mexico				
Adjusted Comprehensive Framework Study	89	89	89	89
Miscellaneous additional depletions	12	12	12	12
Reclamation projects				
Navajo Reservoir evaporation	26	26	26	26
Animas-La Plata	0	0	14	34
San Juan-Chama	110	110	110	110
Navajo Indian irrigation	127	208	267	267
Hammond	8	10	10	10
Hogback Extension	5	10	10	10
Jicarilla Apache	0	3	3	3
Utah International, Inc. (private right)	27	39	39	39
Navajo Reservoir contracts (temporary)				
Public Service Company of New Mexico	16	16	16	0
Utah International, Inc.	0	35	35	35
Gallup-Navajo Indian	0	10	14	18
Not identified	0	10	10	10
Total depletions	420	578	655	663
Evaporation, storage units	58	58	58	58
Total	478	636	713	721
State share of 5.8 million acre-foot yield	647	647	647	647
Remaining water available	169	11	-66	-74
Utah				
Comprehensive Framework Study	664	664	664	664
Miscellaneous additional depletions				
Irrigation and stock	1	1	1	1
Municipal	2	3	5	7
Minerals	1	1	1	1
Reclamation projects				
Central Utah Project				
Bonneville Unit	32	136	166	166
Upalco Unit	0	3	12	12
Jensen Unit	4	15	15	15
Uintah Unit	0	0	28	28
Emery County	11	8	8	8
Gallup-Navajo Indian	0	1	1	1
Ute Indian lands	4	20	84	84
Division of Water Resources projects	11	16	20	24
Thermal electric powerplants				
Emery County	24	30	36	36
Conversion of irrigation to power	-7	-7	-10	-10
Other Utah Power & Light Company plants	0	0	6	12
Deseret Generation Co-op	0	6	12	12
Municipal and industrial				
White River Dam	0	6	6	6
Oil shale	0	1	20	30
Tar sands	0	6	18	30
Total depletions	747	910	1,093	1,127
Evaporation, storage units	120	120	120	120
Total	867	1,030	1,213	1,247
State share of 5.8 million acre-foot yield	1,322	1,322	1,322	1,322
Remaining water available	455	292	109	75
Upper Colorado River Basin totals				
Total depletions	3,489	4,099	4,677	4,870
Evaporation, storage units	520	520	520	520
Total	4,009	4,619	5,197	5,390
5.8 million acre-foot yield	5,800	5,800	5,800	5,800
Remaining water available	1,791	1,181	603	410

Table A
CRSS projected depletions[1]
(Unit--1,000 acre-feet/year)

Lower Basin projects	1983	1990	2000	2010
Nevada				
Southern Nevada Water Project				
Las Vegas Valley	79	143	203	225
Boulder City, Nev.	4	6	7	8
Lake Mead National Recreation Area	1	1	1	1
Miscellaneous users above Hoover Dam	1	1	1	1
Mohave Steamplant, Southern California Edison Company	17	18	22	0
Fort Mohave Indian Reservation	0	4	8	8
Laughlin and miscellaneous users below Hoover Dam	.0	5	7	7
Total	102	178	249	250
Arizona				
Imperial Wildlife Refuge	0	13	13	13
Havasu Wildlife Refuge	39	37	37	37
Fort Mohave Indian Reservation	53	60	60	60
Kingman, Boulder Canyon Project	0	0	9	18
Mohave Valley Irrigation and Drainage District	31	30	41	41
Lake Havasu Irrigation and Drainage District	8	14	14	14
Central Arizona Project	0	1,515	1,488	1,464
Colorado River Indian Reservation	333	383	398	398
Cibola Wildlife Refuge	8	17	17	17
Gila Project	511	450	450	450
Welton-Mohawk Division				
Yuma Mesa Division				
City of Yuma	8	13	18	23
Yuma Project and Yuma Auxiliary Project	237	212	212	212
Cocopah Indian Reservation	1	2	2	2
Other uses	62	54	41	51
Protective and Regulatory Pumping Unit[2]	-24	0	0	0
Yuma Mesa Outlet Drain[2]	-27	0	0	0
Total	1,240	2,800	2,800	2,800
California				
City of Needles	2	1	1	1
Metropolitan Water District	713	519	498	498
Fort Mohave Indian Reservation	31	9	9	9
Chemehuevi Indian Reservation	0	5	8	8
Colorado River Indian Reservation	6	15	33	33
Palo Verde Irrigation District	457	423	423	423
Yuma Project				
Indian Unit	40	31	31	31
Bard Unit	48	28	28	28
Return flow	-28	0	0	0
Imperial Irrigation District	2,596	3,033	3,033	3,033
Coachella Valley Water District	425	485	485	485
Imperial and Coachella return flow	0	-18	-18	-18
Coachella Canal lining		-132	-132	-132
Other uses	21	1	1	1
Total	4,311	4,400	4,400	4,400

1/ From the 1982 Supreme Court Decree Accounting (Arizona vs. California, March 9, 1964). The figures represent measured diversions less measured return flow which can be assigned to a specific project. The figures do not include commingled or unmeasured return flows, thus may not be consistent with estimates of future consumptive use.

2/ Commingled return flow from the Yuma Mesa Division, Gila Project; Valley Division, Yuma Project; and Unit B, Yuma Auxiliary Project.